

SMALL ELECTRODE FOR A
CHALCOGENIDE SWITCHING DEVICE
AND METHOD FOR FABRICATING SAME

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BACKGROUND OF THE INVENTION

1. Field Of The Invention

The present invention relates generally to semiconductor fabrication techniques and, more particularly, to a method for fabricating small electrodes for use with a chalcogenide switching device, such as, for example, a chalcogenide memory cell.

2. Background Of The Related Art

Microprocessor-controlled integrated circuits are used in a wide variety of applications. Such applications include personal computers, vehicle control systems, telephone networks, and a host of consumer products. As is well known, microprocessors are essentially generic devices that perform specific functions under the control of a software program. This program is stored in a memory device coupled to the microprocessor. Not only does the microprocessor access a memory device to retrieve the program instructions, it also stores and retrieves data created during execution of the program in one or more memory devices.

There are a variety of different memory devices available for use in microprocessor-based systems. The type of memory device chosen for a specific function within a microprocessor-based system depends largely upon what features of the memory are best suited to perform the particular function. For instance, volatile memories, such as dynamic random access memories (DRAMs), must be continually powered in order to retain their contents, but they tend to provide greater

storage capability and programming options and cycles than non-volatile memories, such as read only memories (ROMs). While non-volatile memories that permit limited reprogramming exist, such as electrically erasable and programmable "ROMs," all true random access memories, i.e., those memories capable of 10^{14} programming cycles are more, are volatile memories. Although 5 one time programmable read only memories and moderately reprogrammable memories serve many useful applications, a true nonvolatile random access memory (NVRAM) would be needed to surpass volatile memories in usefulness.

Efforts have been underway to create a commercially viable memory device, which is both 10 random access and nonvolatile, using structure changing memory elements, as opposed to charge storage memory elements used in most commercial memory devices. The use of electrically writable and erasable phase change materials, i.e., materials which can be electrically switched between generally amorphous and generally crystalline states or between different resistive states 15 while in crystalline form, in memory applications is known in the art and is disclosed, for example, in U.S. Pat. No. 5,296,716 to Ovshinsky et al., the disclosure of which is incorporated herein by reference. The Ovshinsky patent is believed to indicate the general state of the art and to contain a discussion of the general theory of operation of chalcogenide materials, which are a particular type of structure changing material.

As disclosed in the Ovshinsky patent, such phase change materials can be electrically 20 switched between a first structural state, in which the material is generally amorphous, and a second structural state, in which the material has a generally crystalline local order. The material may also be electrically switched between different detectable states of local order across the

entire spectrum between the completely amorphous and the completely crystalline states. In
other words, the switching of such materials is not required to take place in a binary fashion
between completely amorphous and completely crystalline states. Rather, the material can be
switched in incremental steps reflecting changes of local order to provide a "gray scale"
5 represented by a multiplicity of conditions of local order spanning the spectrum from the
completely amorphous state to the completely crystalline state.

These memory elements are monolithic, homogeneous, and formed of chalcogenide
material typically selected from the group of Te, Se, Sb, Ni, and Ge. This chalcogenide material
10 exhibits different electrical characteristics depending upon its state. For instance, in its
amorphous state the material exhibits a higher resistivity than it does in its crystalline state. Such
chalcogenide materials can be switched between numerous electrically detectable conditions of
varying resistivity in nanosecond time periods with the input of picojoules of energy. The
resulting memory element is truly non-volatile. It will maintain the integrity of the information
15 stored by the memory cell without the need for periodic refresh signals, and the data integrity of
the information stored by these memory cells is not lost when power is removed from the device.
The memory material is also directly overwritable so that the memory cells need not be erased,
i.e., set to a specified starting point, in order to change information stored within the memory
cells. Finally, the large dynamic range offered by the memory material theoretically provides for
20 the gray scale storage of multiple bits of binary information in a single cell by mimicking the
binary encoded information in analog form and, thereby, storing multiple bits of binary encoded
information as a single resistance value in a single cell.

The operation of chalcogenide memory cells requires that a region of the chalcogenide memory material, called the "active region," be subjected to a current pulse to change the crystalline state of the chalcogenide material within the active region. Typically, a current density of between about 10^5 and 10^7 amperes/cm² is needed. To obtain this current density in a commercially viable device having at least 64 million memory cells, for instance, the active region of each memory cell must be made as small as possible to minimize the total current drawn by the memory device. Currently, chalcogenide memory cells are fabricated by first creating a diode in a semiconductor substrate. A lower electrode is created over the diode, and a layer of dielectric material is deposited onto the lower electrode. A small opening is created in the dielectric layer. A second dielectric layer, typically of silicon nitride, is then deposited onto the dielectric layer and into the opening. The second dielectric layer is typically about 40 Angstroms thick. The chalcogenide material is then deposited over the second dielectric material and into the opening. An upper electrode material is then deposited over the chalcogenide material.

A conductive path is then provided from the chalcogenide material to the lower electrode material by forming a pore in the second dielectric layer by a process known as "popping." Popping involves passing an initial high current pulse through the structure to cause the second dielectric layer to breakdown. This dielectric breakdown produces a conductive path through the memory cell. Unfortunately, electrically popping the thin silicon nitride layer is not desirable for a high density memory product due to the high current and the large amount of testing time required. Furthermore, this technique may produce memory cells with differing operational characteristics, because the amount of dielectric breakdown may vary from cell to cell.

The active regions of the chalcogenide memory material within the pores of the dielectric material created by the popping technique are believed to change crystalline structure in response to applied voltage pulses of a wide range of magnitudes and pulse durations. These changes in crystalline structure alter the bulk resistance of the chalcogenide active region. Factors such as 5 pore dimensions (e.g., diameter, thickness, and volume), chalcogenide composition, signal pulse duration, and signal pulse waveform shape may affect the magnitude of the dynamic range of resistances, the absolute endpoint resistances of the dynamic range, and the voltages required to set the memory cells at these resistances. For example, relatively thick chalcogenide films, e.g., 10 about 4000 Angstroms, result in higher programming voltage requirements, e.g., about 15-25 volts, while relatively thin chalcogenide layers, e.g., about 500 Angstroms, result in lower programming voltage requirements, e.g., about 1-7 volts. Thus, to reduce the required programming voltage, it has been suggested that the cross-sectional area of the pore should be 15 reduced to reduce the size of the chalcogenide element.

The energy input required to adjust the crystalline state of the chalcogenide active region of the memory cell is directly proportional to the minimum lateral dimension of the pore. In other words, programming energy decreases as the pore size decreases. Conventional chalcogenide memory cell fabrication techniques provide a minimum lateral pore dimension, e.g., the diameter or width of the pore, that is limited by the photolithographic size limit. This 20 results in pore sizes having minimum lateral dimensions down to approximately 1 micron.

The present invention is directed to overcoming, or at least reducing the affects of, one or more of the problems set forth above.

SUMMARY OF THE INVENTION

In accordance with one aspect of the present invention, there is provided a memory cell.

The memory cell includes an access device that is formed on a semiconductor substrate. A layer of dielectric material is disposed on the access device. The layer of dielectric material has a port therein. The pore is smaller than the photolithographic limit. A first layer of conductive material is disposed within the pore to form a first electrode. A layer of structure changing material is disposed on the first electrode. A second layer of conductive material is disposed on the layer of structure changing material to form a second electrode.

In accordance with another aspect of the present invention, there is provided a memory array. The memory array includes a plurality of memory cells. Each memory cell includes an access device that is formed on a semiconductor substrate. A layer of dielectric material is disposed on the access device. The layer of dielectric material has a pore therein. The pore is smaller than the photolithographic limit. A first layer of conductive material is disposed within the pore to form a first electrode. A layer of structure changing material is disposed on the first electrode. A second layer of conductive material is disposed on the layer of structure changing material to form a second electrode. The memory array also includes a grid that is coupled to the plurality of memory cells. The grid is formed by a first plurality of conductive lines that generally extend in a first direction and a second plurality of conductive lines that generally extend in a second direction.

In accordance with still another aspect of the present invention, there is provided a method of fabricating a memory cell. The method includes the steps: (a) forming an access

device on a semiconductor substrate; (b) depositing a layer of dielectric material on the access device; (c) forming a pore in the layer of dielectric material, where the pore is smaller than the photolithographic limit; (d) depositing a first layer of conductive material within the pore to form a first electrode; (e) depositing a layer of structure changing material on the first electrode; and 5 (f) depositing a second layer of conductive material on the layer of structure changing material to form a second electrode.

In accordance with yet another aspect of the present invention, there is provided a method of fabricating a memory array. The method includes the steps of (a) forming an access device on 10 a semiconductor substrate; (b) forming a first plurality of conductive lines, where each of the first plurality of conductive lines is coupled to respective access devices; (c) depositing a layer of dielectric material on the access device; (d) forming a pore in the layer of dielectric material, where the pore is smaller than the photolithographic limit; (e) depositing a first layer of conductive material within the pore to form a first electrode; (f) depositing a layer of structure changing material on the first electrode; (g) depositing a second layer of conductive material on 15 the layer of structure changing material to form a second electrode; and (h) forming a second plurality of conductive lines, where each of the second plurality of conductive lines is coupled to respective second electrodes.

20 In accordance with a further aspect of the present invention, there is provided a method of fabricating an array of pores. The method includes the steps of (a) forming a mask over a layer of dielectric material, where the mask has a plurality of windows therein exposing portions of the layer of dielectric material, and where the windows are sized at the photolithographic limit; (b)

forming a spacer within each of the windows, where each spacer covers a peripheral portion of the respective exposed portion of the layer of dielectric material to create a second window that exposes a portion of the layer of dielectric material smaller than the photolithographic limit; and
5 (c) removing the exposed portions of the layer of dielectric material created by the second windows to create the pores.

In accordance with an even further aspect of the present invention, there is provided a memory cell. The memory cell includes an access device that is formed on a semiconductor substrate. A layer of dielectric material is disposed on the access device. The layer of dielectric material has a pore therein. The pore is formed by forming a mask over the layer of dielectric material. The mask has a window therein which exposes a portion of the layer of dielectric material. The window is sized at the photolithographic limit. A spacer is formed within the window. The spacer covers a peripheral portion of the exposed portion of the layer of dielectric material to create a second window exposing a portion of the layer of dielectric material smaller than the photolithographic limit. The exposed portion of the layer of dielectric material created by the second window is removed to create the pore. A first layer of conductive material is disposed within the pore to form a first electrode. A layer of structure changing material is disposed on the first electrode. A second layer of conductive material is disposed on the layer of structure changing material to form a second electrode.

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DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

Fig. 1 illustrates a schematic depiction of a substrate containing a memory device which includes a memory matrix and peripheral circuitry;

Fig. 2 illustrates an exemplary schematic depiction of the memory matrix or array of Fig.

5 1;

Fig. 3 illustrates an exemplary memory cell having a memory element, such as a resistor, and an access device, such as a diode;

10 Fig. 4 illustrates a top view of a portion of a semiconductor memory array;

15 Fig. 5 illustrates a cross-sectional view of an exemplary memory cell at an early stage of fabrication;

Fig. 6, Fig. 7, and Fig. 8 illustrate the formation of a spacer and a small pore for the exemplary memory element;

Fig. 9 illustrates the small pore of the memory element;

20 Fig. 10 and Fig. 11 illustrate the formation of an electrode in the small pore;

Fig. 12 illustrates the deposition of memory material over the lower electrode;

Fig. 13 illustrates the deposition of the upper electrode of the memory cell;

Fig. 14 illustrates the deposition of an insulative layer and an oxide layer over the upper electrode of the memory cell; and

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Fig. 15 illustrates the formation of a contact extending through the oxide and insulative layer to contact the upper electrode.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

10 Turning now to the drawings, and referring initially to Fig. 1, a memory device is illustrated and generally designated by a reference numeral 10. The memory device 10 is an integrated circuit memory that is advantageously formed on a semiconductor substrate 12. The memory device 10 includes a memory matrix or array 14 that includes a plurality of memory cells for storing data, as described below. The memory matrix 14 is coupled to periphery circuitry 16 by the plurality of control lines 18. The periphery circuitry 16 may include circuitry for addressing the memory cells contained within the memory matrix 14, along with circuitry for storing data in and retrieving data from the memory cells. The periphery circuitry 16 may also include other circuitry used for controlling or otherwise insuring the proper functioning of the memory device 10.

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20 A more detailed depiction of the memory matrix 14 is illustrated in Fig. 2. As can be seen, the memory matrix 14 includes a plurality of memory cells 20 that are arranged in generally perpendicular rows and columns. The memory cells 20 in each row are coupled

together by a respective word line 22, and the memory cells 20 in each column are coupled together by a respective digit line 24. Specifically, each memory cell 20 includes a word line node 26 that is coupled to a respective word line 22, and each memory cell 20 includes a digit line node 28 that is coupled to a respective digit line 24. The conductive word lines 22 and digit lines 24 are collectively referred to as address lines. These address lines are electrically coupled to the periphery circuitry 16 so that each of the memory cells 20 can be accessed for the storage and retrieval of information.

5 Fig. 3 illustrates an exemplary memory cell 20 that may be used in the memory matrix 10 14. The memory cell 20 includes a memory element 30 which is coupled to an access device 32. In this embodiment, the memory element 30 is illustrated as a programmable resistive element, and the access device 32 is illustrated as a diode. Advantageously, the programmable resistive element may be made of a chalcogenide material, as will be more fully explained below. Also, the diode 32 may be a conventional diode, a zener diode, or an avalanche diode, depending upon 15 whether the diode array of the memory matrix 14 is operated in a forward biased mode or a reverse biased mode. As illustrated in Fig. 3, the memory element 30 is coupled to a word line 22, and the access device 32 is coupled to a digit line 24. However, it should be understood that connections of the memory element 20 may be reversed without adversely affecting the operation of the memory matrix 14.

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As mentioned previously, a chalcogenide resistor may be used as the memory element 30. A chalcogenide resistor is a structure changing memory element because its molecular order may be changed between an amorphous state and a crystalline state by the application of electrical

current. In other words, a chalcogenide resistor is made of a state changeable material that can be switched from one detectable state to another detectable state or states. In state changeable materials, the detectable states may differ in their morphology, surface typography, relative degree of order, relative degree of disorder, electrical properties, optical properties, or combinations of one or more of these properties. The state of a state changeable material may be detected by measuring the electrical conductivity, electrical resistivity, optical transmissivity, optical absorption, optical refraction, optical reflectivity, or a combination of these properties. In the case of a chalcogenide resistor specifically, it may be switched between different structural states of local order across the entire spectrum between the completely amorphous state and the completely crystalline state.

The previously mentioned Ovshinsky patent contains a graphical representation of the resistance of an exemplary chalcogenide resistor as a function of voltage applied across the resistor. It is not unusual for a chalcogenide resistor to demonstrate a wide dynamic range of attainable resistance values of about two orders of magnitude. When the chalcogenide resistor is in its amorphous state, its resistance is relatively high. As the chalcogenide resistor changes to its crystalline state, its resistance decreases.

As discussed in the Ovshinsky patent, low voltages do not alter the structure of a chalcogenide resistor, while higher voltages may alter its structure. Thus, to "program" a chalcogenide resistor, i.e., to place the chalcogenide resistor in a selected physical or resistive state, a selected voltage in the range of higher voltages is applied across the chalcogenide resistor, i.e., between the word line 22 and the digit line 24. Once the state of the chalcogenide

resistor has been set by the appropriate programming voltage, the state does not change until another programming voltage is applied to the chalcogenide resistor. Therefore, once the chalcogenide resistor has been programmed, a low voltage may be applied to the chalcogenide resistor, i.e., between the word line 22 and the digit line 24, to determine its resistance without changing its physical state. As mentioned previously, the addressing, programming, and reading of the memory elements 20 and, thus, the application of particular voltages across the word lines 22 and digit lines 24, is facilitated by the periphery circuitry 16.

The memory cell 20, as illustrated in Fig. 3, may offer significant packaging advantages as compared with memory cells used in traditional random access and read only memories. This advantage stems from the fact that the memory cell 20 is a vertically integrated device. In other words, the memory element 30 may be fabricated on top of the access device 32. Therefore, using the memory cell 20, it may be possible to fabricate an X-point cell that is the same size as the crossing area of the word line 22 and the digit line 24, as illustrated in Fig. 4. However, the size of the access device 32 typically limits the area of the memory cell 20, because the access device 32 must be large enough to handle the programming current needed by the memory element 30.

As discussed previously, to reduce the required programming current, many efforts have been made to reduce the pore size of the chalcogenide material that forms the memory element 30. These efforts have been made in view of the theory that only a small portion of the chalcogenide material, referred to as the "active region," is structurally altered by the programming current. However, it is believed that the size of the active area of the chalcogenide

memory element 30 may be reduced by reducing the size of an electrode which borders the chalcogenide material. By reducing the active area and, thus, the required programming current, the size of the access device may be reduced to create an X-point cell memory. For example, a cell with a chalcogenide cross-sectional area equivalent to a circle with an $0.2\mu\text{m}$ diameter might 5 require a current pulse of 2mA to program to high resistance state. If the diameter of the cell is reduced to $0.1\mu\text{m}$ the current could be reduced to about 0.5mA. Over certain ranges of operation the programming current is directly proportional to the area of the cell.

10 The actual structure of an exemplary memory cell 20 is illustrated in Fig. 15, while a method for fabricating the memory cell 20 is described with reference to Figs. 5-15. It should be understood that while the fabrication of only a single memory cell 20 is discussed below, thousands of similar memory cells may be fabricated simultaneously. Although not illustrated, each memory cell is electrically isolated from other memory cells in the array in any suitable manner, such as by the addition imbedded field oxide regions between each memory cell.

15 In the interest of clarity, the reference numerals designating the more general structures described in reference to Figs. 1-4 will be used to describe the more detailed structures illustrated in Figs. 5-15, where appropriate. Referring first to Fig. 5, the digit lines 24 are formed in or on a substrate 12. As illustrated in Fig. 5, the digit line 24 is formed in the P-type substrate 12 as a heavily doped N+ type trench. This trench may be strapped with appropriate materials to enhance its conductivity. The access device 32 is formed on top of the digit line 24. The illustrated access device 32 is a diode formed by a layer of N doped polysilicon 40 and a layer of P+ doped polysilicon 42. Next, a layer of insulative or dielectric material 44 is disposed on top

of the P+ layer 42. The layer 44 may be formed from any suitable insulative or dielectric material, such as plasma enhanced CVD SiO₂, or PECVD silicon nitride or standard thermal CVD Si_3N_4 .

5 The formation of a small pore in the dielectric layer 44 is illustrated with reference to

Figs. 5-9. First, a hard mask 46 is deposited on top of the dielectric layer 44 and patterned to form a window 48, as illustrated in Fig. 6. The window 48 in the hard mask 46 is

advantageously as small as possible. For instance, the window 48 may be formed at the

photolithographic limit by conventional photolithographic techniques. The photolithographic

10 limit, i.e., the smallest feature that can be patterned using photolithographic techniques, is

currently about $0.2\mu\text{m}$. Once the window 48 has been formed in the hard mask 46, a layer of spacer material 50 is deposited over the hard mask 46 in a conformal fashion so that the upper surface of the spacer material 50 is recessed where the spacer material 50 covers the window 48.

15 Although any suitable material may be used for the spacer material 50, a dielectric material, such CVD amorphous or polycrystalline silicon, may be advantageous.

The layer of spacer material 50 is subjected to an anisotropic etch using a suitable

20 etchant, such as HBr + Cl₂. The rate and time of the etch are controlled so that the layer of spacer material 50 is substantially removed from the upper surface of the hard mask 48 and from a

portion of the upper surface of the dielectric layer 44 within the window 48, leaving sidewall spacers 52 within the window 48. The sidewall spacers 52 remain after a properly controlled

etch because the vertical dimension of the spacer material 50 near the sidewalls of the window 48

is approximately twice as great as the vertical dimension of the spacer material 50 on the surface of the hard mask 46 and in the recessed area of the window 48.

Once the spacers 52 have been formed, an etchant is applied to the structure to form a 5 pore 54 in the dielectric layer 44, as illustrated in Fig. 8. The etchant is an anisotropic etchant that selectively removes the material of the dielectric layer 44 bounded by the spacers 52 until the P+ layer 42 is reached. As a result of the fabrication method to this point, if the window 48 is at the photolithographic limit, the pore 54 is smaller than the photolithographic limit, e.g., on the 10 order of 0.1 μ m. After the pore 54 has been formed, the hard mask 46 and the spacers 52 may be removed, as illustrated in Fig. 9. The hard mask 46 and the spacers 52 may be removed by any suitable method, such as by etching or by chemical mechanical planarization (CMP).

The pore 54 is then filled to a desired level with a material suitable to form the lower 15 electrode of the chalcogenide memory element 30. As illustrated in Fig. 10, a layer of electrode material 56 is deposited using collimated physical vapor deposition (PVD). By using collimated PVD, or another suitable directional deposition technique, the layer of electrode material 56 is formed on top of the dielectric layer 44 and within the pore 54 with substantially no sidewalls. Thus, the layer of electrode material 56 on top of the dielectric layer 44 may be removed, using 20 CMP for instance, to leave the electrode 56 at the bottom of the pore 54, as illustrated in Fig. 11.

It should be understood that the electrode material 56 may be comprised of one or more materials, and it may be formed in one or more layers. For instance, a lower layer of carbon may be used as a barrier layer to prevent unwanted migration between the subsequently deposited

chalcogenide material and the P+ type layer 42. A layer of titanium nitride (TiN) may then be deposited upon the layer of carbon to complete the formation of the electrode 56.

After the lower electrode 56 has been formed, a layer of chalcogenide material 58 may be deposited so that it contacts the lower electrode 56, as illustrated in Fig. 12. Various types of chalcogenide materials may be used to form the chalcogenide memory element 30. For example, chalcogenide alloys may be formed from tellurium, antimony, germanium, selenium, bismuth, lead, strontium, arsenic, sulfur, silicon, phosphorous, and oxygen. Advantageously, the particular alloy selected should be capable of assuming at least two generally stable states in response to a stimulus, for a binary memory, and capable of assuming multiple generally stable states in response to a stimulus, for a higher order memory. Generally speaking, the stimulus will be an electrical signal, and the multiple states will be different states of crystallinity having varying levels of electrical resistance. Alloys that may be particularly advantageous include tellurium, antimony, and germanium having approximately 55 to 85 percent tellurium and 15 to 25 percent germanium, such as $\text{Te}_{56}\text{Ge}_{22}\text{Sb}_{22}$.

If the lower electrode 56 is recessed within the pore 54, a portion of the chalcogenide material 58 will fill the remaining portion of the pore 54. In this case, any chalcogenide material 58 adjacent the pore 54 on the surface of the dielectric layer 44 may be removed, using CMP for instance, to create a chalcogenide element of extremely small proportions. Alternatively, if the lower electrode 56 completely fills the pore 54, the chalcogenide material 58 adjacent the pore 54 may remain, because the extremely small size of the lower electrode 56 still creates a relatively small active area in a vertical direction through the chalcogenide material 58. Because of this

characteristic, even if the lower electrode 56 only partially fills the pore 54, as illustrated, the excess chalcogenide material 58 adjacent the pore 54 need not be removed to create a memory element 30 having an extremely small active area.

5 Regardless of which alternative is chosen, the upper electrode 60 is deposited on top of the chalcogenide material 58, as illustrated in Fig. 13. After the upper electrode 60, the chalcogenide material 58, the dielectric layer 44, and the access device 32 have been patterned and etched to form an individual memory cell 20, a layer of insulative material 62, such as silicon nitride, is deposited over the structure, as illustrated in Fig. 14. A layer of oxide 64 is 10 then deposited over the insulative layer 62. Finally, the oxide layer 64 is patterned and a contact hole 66 is formed through the oxide layer 64 and the insulative layer 62, as illustrated in Fig. 15. The contact hole 66 is filled with a conductive material to form the word line 22.

15 While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.